ON THE AFTER-IMAGES OF SUBLIMINALLY COLORED STIMULI.

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We attempt, in the present paper, to answer the question whether a subliminally colored stimulus may arouse a colored, negative or complementary after-image. This question has been answered in the affirmative both for direct and for indirect vision, and in indirect vision for all three of the retinal zones. Our own experiments, on the other hand, have led us to answer it in the negative. Provided that the subliminally colored stimulus appears on a neutral (black, gray or white) background, and provided that the retina is achromatically adapted, we find no trace of the colored after-image in either direct or indirect vision, with either light or dark adaptation.

Previous Experiments.

1. *Direct Vision.*—In a paper entitled *Das Anpassungsproblem in der Physiologie der Gegenwart* (1904), A. Tschermak compares the course of excitation in the retina with the effects produced by the constant current in a nerve-muscle preparation. The passage is as follows:

"Haben wir doch gerade in der Anwendung des constanten Stromes auf Nerv und Muskel ein vorzügliches didaktisches Mittel, um die Grundbegriffe der allgemeinen Reiz- und Adaptationslehre zu veranschaulichen und einzuprägen. Am besten demonstrieren wir als Gegenstück zugleich die Wirkung eines mässig satten Farbglases auf das Auge: die Phase der Reizwirkung, individuell verschieden lang, und dadurch erinnernd an die verschiedenrasche Adaptation des Praeparates vom Warmfrosch und Kaltfrosch an den constanten Strom — weiterhin das Stadium der vollendeten Adaptation, endlich den gegensinnigen Oeffnungseffect. Nicht minder lehrreich ist die Parallele des subjectiven und des objectiven Erscheinungsgebietes für das Phaenomen des Einschleichens d. h. des Ausbleibens einer sinnfälligen Reizwirkung, wenn der Reiz so langsam anwächst, dass das Adaptationsvermögen folgen kann — gleichwohl hat auch nunmehr Wegfall

des 'Reizes' eine gegensinnige Oeffnungswirkung. Analoges gilt vom Ausschleichen, also vom Ausbleiben eines sinnfälligen Oeffnungseffectes. Zum optischen Versuche schiebt man zweckmässig eine schwach tingierte Glasplatte vor die andere oder benützt einen Keil farbigen Glases."[1]

The observation here briefly mentioned was apparently made in light-adaptation. The observer, we may suppose, looked through a vertical slit in a cardboard screen towards a window. The thin end of the colored glass wedge, viewed through the slit, appeared colorless. The wedge itself was slowly pushed forward — so slowly that progressive adaptation prevented its color from being perceived. Presently the observer turned his eye to the cardboard screen, and there saw the negative colored after-image, the "gegensinnige Oeffnungswirkung" that followed the "Einschleichen des Reizes."[2]

2. *Indirect Vision.*—In the Studies from the Psychological Laboratory of Mount Holyoke College for 1905, Miss G. M. Fernald reports the arousal of colored after-images in the peripheral or black-white zone of the retina. "A further point worth mentioning"—so the passage runs—"is the fact that, in the case of several colors, exposure, beyond the limits where any color is seen, is followed by a very clear [colored] after-image. This was repeatedly found to be true with red, orange, green and blue and often with yellow [stimuli]. This after-image for the first three and for yellow was blue, and for blue a very clear yellow. This may explain the 'gegenfarbige' zone found by Hellpach in his dark-room work, as under those conditions there would have been no way of telling whether the color came exactly at the time of exposure or immediately afterwards."[3] No further details are given.

[1] *Archives des sciences biologiques,* XI., Supplément (*Festschrift* for Professor J. P. Pavloff), 82 f.

[2] The procedure is sketched by H. Abels, *Zeits. f. Psychol.,* XLV., 1907, 86. "Man kann . . . einen schwach gefärbten Glaskeil so langsam vor das Auge schieben, von der Kante gegen den Rücken fortschreitend, dass überhaupt keine Farbenempfindung zustande kommt; und dennoch haben wir bei plötzlichem Entfernen desselben und Betrachten einer indifferent gefärbten Fläche die deutliche Empfindung der komplementären Farbe." Abels is here quoting a conversation with Tschermak; there is no evidence that he himself performed the experiment.

[3] "The Effect of the Brightness of Background on the Extent of the Color Fields and on the Color Tone in Peripheral Vision," *Psychol. Review,* XII., November, 1905, 405.

These observations would, no doubt, have been repeated, and their interpretation discussed by other experimenters, had not Baird published, earlier in the same year, his study of the color sensitivity of the peripheral retina. "There seems to be no doubt," Baird had written, "that Hellpach's zone of complementariness is an artifact, and that its discovery is wholly due to the experimenter's failure to avoid retinal fatigue [chromatic adaptation] in his explorations." [4] Nevertheless, one of the present writers (*T*) made in 1906 a fairly long series of campimetrical observations (some 200 in all) with the view of testing Miss Fernald's conclusion. The colored stimuli were Hering papers, R, Y, G and B; the backgrounds were white, neutral gray and black. In no case was "exposure, beyond the limits where any color is seen," followed by a colored after-image, clear or obscure. All four colors, if they gave an after-image at all, gave a colorless image, indistinguishable from the after-images of gray stimuli—as these gray stimuli themselves were indistinguishable from the colored papers. It therefore seemed probable—indeed, it seemed practically certain—that the Mount Holyoke results were due to a defect of method. Since Baird's disproof of the "gegenfarbige Zone" was deemed complete and final, the Cornell observations were not published.

However, in the following year, 1907, a second paper from the Mount Holyoke laboratory reported the same phenomenon. "At the extreme periphery it sometimes happened: (*a*) that a stimulus which was clearly seen produced no after-image. . . . (*b*) On the other hand there were 118 cases in which a subliminal stimulus produced an after-image which was perfectly distinct in color. . . . That this somewhat unusual result was not the outcome of imagination or suggestion seems proved by the fact that these invisible colors gave rise to their appropriate after-images." [5] The authors, the Misses H. B. Thompson and K. Gordon, found no indication of Hellpach's zone of complementarism. They refer the images to the enhancing influence of a light background.

[4] J. W. Baird, "The Color Sensitivity of the Peripheral Retina," Carnegie Institution of Washington, Publication No. 29, May, 1905, 73.

[5] "A Study of After-Images on the Peripheral Retina," *Psychol. Review*, XIV., March, 1907, 126 f., 129 f.

Again, in 1908, in a continuation of her former study, Miss Fernald writes: "In agreement with the observations already made in our first paper, and later in the work of Miss Thompson and Miss Gordon, our results show that in many cases a characteristic colored after-image follows an unperceived color stimulus. In general this after-image is perfectly clear and distinct. . . . That the phenomena here described are genuine after-images is shown by the fact that the color is in every case the color complementary to the stimulus as [it would be] perceived either in central or in peripheral vision, although the observer was kept in complete ignorance concerning the nature of the stimuli employed, and so had no clew as to what after-image was to be expected in cases in which the [color of the] stimulus was not seen. Moreover, gray and white, though frequently used as stimuli, were never followed by colored after-images."[6] Hellpach here drops out of sight altogether, while the range of the subliminally aroused after-image is extended, from "the extreme periphery," to include both the B–Y and the R–G zones.

New Experiments.

I. *Direct Vision: (a) Light-Adaptation.*

Experiment I.: The Glass Wedge.—We wished to begin our own experiments by repeating Tschermak's observation with the faintly colored glass wedge. However, the difficulty of finding a suitable glass proved to be so great that this Exp. I. was, as a matter of fact, performed last of all. After many delays we were able, through the kind assistance of Professor J. A. Brashear, to secure a wedge of light blue glass, 5 by 20.5 cm., the thin end of which was almost colorless in clear daylight. Although the color might well have been still fainter, we found it possible, with an observation-slit of 22 by 5 mm., and with a white muslin screen stretched between the glass wedge and the white-screened windows from which our illumination was derived, to take observations of 2 to 5 min. duration, in which the wedge was moved, for the practised observers, from 1.5 to 4 cm., and for the unpractised from 5 to 10 cm.

[6] "Studies from the Bryn Mawr College Laboratory: The Effect of the Brightness of Background on the Appearance of Color Stimuli in Peripheral Vision," *Psychol. Review*, XV., January, 1908, 33 ff.

We made no long series of tests, since the question at issue had already been answered, so far as we could answer it, by the following Exps. II.–V. The experiments were, however, carefully conducted. The work was done in a long gray-tinted light-optics room, with achromatic adaptation; the observers were the writers (*T, P*), Mr. L. R. Geissler (*G*), assistant in psychology, and two unpractised students, Mrs. G. L. de Ollogni and Mr. E. M. Stevens; and the experimenter had acquired great skill, from Exps. II. and IV., in moving the wedge slowly and steadily forward. In general, the stimulus-background was black, and the field for the projection of the after-image was white, though these relations were occasionally changed.

As we had expected, there was no trace of color in the after-image; this result was uniform. In control experiments, in which (after a period for the recovery of the eye) the glass was exposed for 30 sec. at the point finally reached in the adaptation experiments, the after-image showed a brief period of dirty orange or brownish yellow, followed by gray.

Experiment II.: The Marbe Color Mixer.—The observations with Tschermak's wedge could not, in any case, be regarded as more than preliminary. For systematic work we employed, first, the Marbe color mixer, which permits the change of a colored sector during rotation of its discs, and thus gives scope for progressive adaptation.

The observer, head in rest, was seated at a distance of 1 m. from a black cardboard screen. The rotating discs were observed through a circular opening, 2 cm. in diameter, cut in the screen at the level of the eyes. The observation was monocular, and was continued for 5 to 7 min. The discs were made up of white, with a sector of colored paper (Zimmermann R, Y, G, B, V); the color at the outset was subliminal for the achromatically light-adapted eye, and was gradually increased in amount as the observation proceeded. The after-image was projected upon a fixation-point marked on a white cardboard dropped in front of the black screen.[1]

[1] For comparative purposes, a few observations were taken with a gray screen, and with projection upon a black or gray background. Nothing new resulted.

The regular observers were *T, P, G,* and Mr. T. Nakashima, graduate scholar in psychology (*N*). A few observations were secured from Professor I. M. Bentley (*B*), and from an unpractised observer, Mr. H. J. Bool; single observations were made by several visitors to the laboratory.

In intention, the procedure was without knowledge. In practice, the experimenter found it impossible, in the early stages of the work, to regulate the size of the colored sector in precise accordance with the course of adaptation. The observer was therefore instructed to tap on the table with a pencil whenever he perceived a color in the stimulus. If a tap was given, the experimenter ran the colored sector back through five or ten degrees, and continued the experiment from that point. The results of these interrupted observations varied, according to the frequency of the taps and the insistence of the color in the stimulus. The following are typical records.

A. No Color Seen in Stimulus.

Observer.	Color in Disc.	After-image.	Duration of Obs.
T	205° B	Gray	7 min.
	180° V	Gray	6 min.
P	120° G	Gray	5 min.
	140° V	Gray	5 min. 15 sec.
G	135° R	Gray	6 min.
B	190° B	Gray	6 min.

After a period for recovery, the stimuli were exposed at their final color-strength for 30 sec., and the after-image was projected as before. The results, in the above instances, were as follows:

Observer.	Color Seen.	After-image.
T	Blue	Brownish yellow
	Bluish violet	Dirty olive yellow
P	Green	Pink
	Bluish violet	Dingy yellow
G	Red	Gray
B	Blue	Clear yellow

B. Color Seen in Stimulus.

Observer.	Color in Disc.	After-image.	Duration of Obs.
T	140° G	Gray	5 min.
G	120° Y	Dark blue	5 min.
	220° B	? Orangish	7 min.
N	155° R	Gray	7 min.
	130° Y	Blue	6 min.

The control experiments, with 30 sec. exposure, gave the results:

Observer.	Color Seen.	After image.
T	Green	Purple
G	Yellow	Dark blue
	Blue	Yellow
N	Pink	? Violet
	Yellow	Blue

The general results of these experiments may be summed up in the following propositions.

1. With every one of our observers, regular and casual, we have been able to raise a color-component in the stimulus from a subliminal to a normally supraliminal value, while the stimulus appeared throughout as gray. In no instance of this kind has the observer found the complementary color in the after-image. Our results thus stand in direct opposition to the observation of Tschermak.

2. There are, however, marked individual differences among the observers. In the 7 min. which represented the limit of our observations, it was difficult, with *G* and *N*, to increase the color-component, without detection, to a normally supraliminal amount: with *T*, *P* and *B* there was no such difficulty. The control images, on the other hand, were obtained most readily from *T* and *P*.

The observer *N* is of the subjective type, and is often misled by an "expected" or "imagined" color. Thus a disc containing 175° G was seen as B with a rim of Y; the after-image, after 6 min., was a Y of irregular form, larger than the stimulus. We recur to these "imagined" colors later. The remaining observers were of a distinctly objective type.

3. There were also, as might be expected, marked differences in the "coloring power" of the Zimmermann papers. Experiments of the form *A* were easiest with B, less easy with V; then follow in order R, G, Y. The last-mentioned color, indeed, gave results only with entirely naive and unpractised observers. The R and G, when seen as color, usually appeared first as Y.

4. As a rule, the after-images, whether colored or gray, developed very slowly. The gray images, in particular, might appear only after a blank interval of 15 to 30 sec. They usually showed

two stages, dark and light. The colored images, both of the regular and of the control experiments, passed off as gray.

Experiment III.: The Color Mixer with Unchanged Discs.—So far we have followed and systematised Tschermak's method; the amount of color in the stimulus has increased, during the single observation, and has been compensated by a progressive adaptation. In the present experiments the amount of color in the discs is increased from subliminal to normally supraliminal, step by step, in successive observations.

The rotating discs were observed, as before, through a circular opening in a black or neutral gray screen. The discs themselves were made up of neutral gray (identical with that of the screen), with a colored sector (Hering R, Y, G, B). The stimulus was fixated for 1 min., and the after-image was projected upon a neutral gray or black background. *P, G* and *N* served as regular observers: a few observations were also taken from *B* and *T*. The following are typical results.

Observer.	Color in Disc.	Color Seen.	Color in After-image.
G	4° G	None	None
	10° G	Green	None
	14° G	Green	Pinkish
N	9° B	None	None
	12° B	None	None
	20° B	? Pinkish	None
	50° B	Blue	Yellow
P	6° R	? Ruddy	None
	10° R	Red	None
	30° R	Red	Green
T	6° Y	None	None
	12° Y	? Yellowish	None
	20° Y	Yellow	Dark blue

In the above observations, the black screen and the neutral gray background were employed. Other arrangements of screen and background gave similar results.

In no case was a colored after-image obtained from a subliminally colored stimulus. On the contrary, the image appeared only when the stimulus-color was distinctly supraliminal.

(*b*) *Dark-Adaptation.*

Experiment IV.: The Glass Wedge.—Besides furnishing the light blue wedge of Exp. I., Professor Brashear supplied us with smaller and more highly colored wedges of claret, red, orange, green and blue glass. With these, or with combinations of them, we proceeded as follows.

A sheet of ground glass was inserted in the Hering window of a large dark-room: the width of the strip could be regulated at will. Some 2.50 m. before the window was a table, on which stood a large screen of white cardboard. Immediately behind a vertical slit in this screen (3 by 25 mm.) lay a grooved strip of wood, in which the wedge or wedges could be moved. Observations were made in dark-adaptation. The thick end of the wedge was first shown; it appeared as black or as dark gray. The wedge was then moved along, very slowly: if the observer saw its color, he tapped with a pencil, and the experimenter withdrew it a trifle, to start again after a few seconds. At a given signal, the observer looked away from the slit to the cardboard screen, or to a black surface directly below the screen, and watched the development of the after-image. The regular observers were *T, P, G* and *N;* a few observations were also made by *B.*

Owing to the difficulty of procuring the large glass wedge of Exp. I., these dark-room observations were the first taken. And, in our desire to do justice to Tschermak's method, we spent more time and trouble upon them than we like to recall. The observer's head was fixed securely in a head-rest; the height of the screen was carefully adjusted; generous time was allowed for adaptation; the admission of light was rigorously controlled, beforehand, by the experimenter; the uniform movement of the wedge was assiduously practised. We were rewarded, however, by the unequivocal character of the results. Though observation might be continued for 5 min.; though during this period the observer might tap his glimpse of color no less than seven times; and though in the control experiments, with immediate observation of the part of the wedge finally exposed, a good complementary after-image might be obtained in

20 sec.: we did not once, in the course of the principal experiments, obtain a record of color in the after-image. Sometimes the after-image failed to appear at all; more often it appeared, and obstinately remained, as gray.

The duration of a single observation varied between the limits of 2 min. 30 sec. and 5 min.; most of the exposures were about 3 min. The number of taps varied from 0 to 7; the average for all observers was 4. The color was thus much more insistent than in Exp. II. — partly, no doubt, because the range of possible movement was only about one-third of that allowed by the Marbe mixer. In the control experiments, *T* and *P* obtained the colored after-image fairly easily; *G*, *N* and *B* often failed to secure it.

Experiment V.: Colored Papers.—These observations were also made in the dark-room and with dark-adaptation. A number of Milton-Bradley colored papers, 4 by 8 cm., were pasted upon white, neutral gray and black grounds. The Hering window was so adjusted that, for the experimenter, the color of the particular paper exposed was just subliminal. The observers (*T, P, G, N* and occasionally *B*) fixated the colored strip at a distance of 1 m. for 40 sec., and projected the after-image upon a white, neutral gray or black surface. All possible combinations of stimulus-ground and projection-ground were employed.

The observer was instructed to report the quality of the stimulus as it appeared at first fixation, and to mention any qualitative change that it might undergo in the course of an observation. In most cases the color was subliminal; and the subliminally colored stimulus never gave a colored after-image. In the cases in which the color of the strip was seen, the after-image was sometimes colored, sometimes gray.

The direct judgment of color under these conditions is extremely difficult, and the observer is sorely tempted to avail himself of secondary criteria—brightness, velvetiness, depth, shimmer, etc. An observer of the objective type soon learns, however, to distinguish between vision and imagination: "I can see nothing," he will say, "but I should guess that it is red" or what not. The guesses were confined—probably from the analogy of the immediately preceding Exp. III.—to the four colors R, Y, G, B; and, as we had the full set of Milton-Bradley papers at our disposal, they were more

often wrong than right.[8] Their influence upon the after-image appeared only in the case of the subjective observer *N*. Thus, R seen on W was judged by *N* to be "red or blue"; and the after-image, also on W, was a large irregular disc of yellow. R seen on Bk was judged to be "bluish"; and the after-image, on gray, was green-blue with a vague yellow rim. B seen on W was judged "blue or red"; and the after-image, on gray, was red above and blue below, with a yellow patch between. It is noteworthy that here, as in Exp. II., after-images of the "supposed" or "imagined" color invariably differed in form and size from those of the true color. The observer did not realise the significance of this difference, though in time he would doubtless have learned to use it as a secondary criterion.

II. *Indirect Vision.*

We have already mentioned the experiments made by *T* in 1906 with the view of testing the conclusions of Miss Fernald's first paper. The observations were rigorously confined to the Bk–W zone, and their outcome was definitely negative. In the meantime, however, the arousal of a colored after-image by a subliminally colored stimulus had been maintained for both the B–Y and the R–G zones. Unsystematic observations made in the Cornell Laboratory failed to confirm this result. It seemed worth while, however, to obtain further testimony; and Professor J. W. Baird, of the University of Illinois, very kindly consented to investigate the subject.[9]

[8] One of the observers remarked that the experiments showed—what he had never fully understood before—how it is that a case of partial color-blindness may remain undetected both by the color-blind person himself and by the normal persons in his surroundings. In principle, the remark was correct enough; but in practice the observer would have had to revise and extend his criteria very considerably.

[9] All the observations in indirect vision mentioned in this paper were carried out with light-adaptation. Peripheral after-images in dark-adaptation are practically non-existent. In *op. cit.*, 56 f., Baird writes: "After-images—in the ordinary sense of the term—were almost invariably absent from our experiments. They were reported in less than one per cent. of our exposures; and when they did occur, they were aroused by the stimulation of paracentral, never of peripheral, regions of the retina." And in a personal letter he adds: "There is an interesting difference of function in

The experiments were carried out by means of a simplified form of the Zimmermann perimeter, which permitted an accurate record of the degree of eccentricity at which the stimulus was exposed. Exploration was confined to the horizontal nasal meridian of each eye. The stimulus was a beam of light from an electric (16 c. p.) lamp, transmitted through appropriate combinations of gelatines and colored glasses; the colors employed were (non-equated) B and Y, R and G. Six of the most reliable laboratory students[10] acted as observers, and Professor Baird had personal charge of the entire work. The after-images were projected upon white, gray and black grounds. The experiments proper were preceded by a careful determination of the outermost limits of color vision for the stimuli used, and all pains were taken to avoid chromatic adaptation.

The following may serve as a sample of method and results.

Determination of Outermost Limits of Blue Vision: Observer Bu.
Right Eye.

Preliminary.		Series 1.	
90°–75°	Nothing	72°–58°	Black
70°–55°	Dark gray	56°–50°	Bluish
50°–45°	Bluish	48°–	Blue
40°–	Blue		

Series 2.		Series 3.	
75°–63°	Black	73°–61°	Very dark gray
61°–53°	Bluish	59°–	Bluish
51°–	Blue		

Outermost limit (bluish or blue): 61°.

Left Eye.[11]

90°–65°	Nothing	62°–50°	Black
60°–40°	Dark gray	48°–44°	Bluish
35°–	Bluish to blue	42°–	Blue
60°–48°	Black	58°–44°	Black
46°–	Bluish	42°–	Bluish

Outermost limit (bluish or blue): 48°.

the peripheral retina in light-adaptation and in dark-adaptation. In the latter case, after-images—both uncolored and colored—are faint or wholly lacking. In the former case they are readily perceptible. Yet even in light-adaptation they are less perceptible than are the primary images aroused by the given stimuli."

[10] The Misses M. Miller, A.B., and B. Scoggin: and Messrs. C. B. Busey, A.B., R. Garrett, O. L. Herndon and A. C. Schertz, A.B.

[11] The visual acuity of the left eye was less than that of the right.

Perimetrical Experiments.

Stimulus.	Duration.	Perception.	After-image.
90° Right	30 sec.	Nothing	None
90° Left	30 sec.	Nothing	None
80° Right	30 sec.	Nothing	None
80° Left	30 sec.	Nothing	None
70° Right	40 sec.	Dark gray	None
70° Left	40 sec.	Nothing	None
60° Right	40 sec.	Bluish, then black	None
60° Left	40 sec.	Gray	None
50° Right	40 sec.	Dark bluish, then gray	Yellowish, then gray
50° Left	40 sec.	Trace of bluish, then gray	Gray

It does not seem necessary to print the full set of results, though the data are at the disposal of anyone who may wish to consult them. The net outcome of the enquiry, in Professor Baird's words, is as follows: "In not a single instance did any stimulus give a colored after-image at a retinal region where it gave an uncolored image," *i. e.,* where it was seen as black or gray. He proceeds: "I have tried every variation of the conditions (with exclusion of chromatic adaptation) which my ingenuity could devise; and the result is in every instance negative, so far as the contention of the Misses Fernald, Thompson and Gordon is concerned."

Criticism and Interpretation.

1. The positive outcome of Tschermak's observations with the glass wedge must, in our opinion, be explained by the prepossession of the observer and the roughness of the method employed. Had Tschermak been in doubt as regards the after-image, he would have had recourse to a more refined instrument, as the Marbe color-mixer. And had he adopted a better method, we cannot doubt, on our side, that the outcome of his observations would have been negative. We may, perhaps, venture to express the hope that he will now submit his hypothesis to a stricter test.

2. It is less easy to account for the peripheral results. The *experimentum crucis,* in positive regard, would seem to be the production of a colored after-image, in the achromatically adapted eye, at a point lying well beyond the limits of B–Y vision. It must be remembered that in all liminal determinations an unnoticed variation in physical or physiological conditions, or in the conditions of

attention, may lead to a serious variation of numerical result. It is, for instance, exceedingly doubtful if any but the most careful and most highly practised observers can maintain their fixation so accurately as to ensure a precise localisation of the retinal area affected by a given stimulus. Moreover, we are here dealing with a retinal function which tails off gradually from center to periphery: so that a very slight shift of regard, or a momentary lapse of attention, or a minimal change in adaptation or in illumination may be enough to vitiate an observation. An illustration may be taken from the records of the observer *Bu.*, quoted above. The outermost limit of B-vision, in the left eye, was determined as 48°. Nevertheless, the observer reported, in the experiments proper, a "trace of bluish, then gray" with the stimulus at 50°. There was no colored after-image. But suppose a tinge of blue-adaptation: then we might have had a perception of gray, and a yellow after-image; and we should still have been, apparently, beyond the limit of B–Y vision. It was only the care taken to avoid chromatic adaptation that prevented the positive result.

It is, of course, precisely this crucial experiment which is described affirmatively by Miss Fernald in 1905,[12] and which came out negatively in *T*'s experiments of 1906. The question then arises as to the accuracy of determination of the zonal limits. And on this point we may quote specimen results from Miss Fernald's tables.

1. R stimulus on light gray background.[13]

10°–73°	Stimulus uniformly seen as red.
74.5°	*No color seen.*
76°	Red seen in two observations.
80°	Red seen in four, no color seen in two observations.
82.5°	No color seen.
84°	No color seen.

[12] We follow the phrasing of the *Psychol. Review* of 1905: "Exposure, beyond the limits where any color is seen, is followed by a very clear after-image." In the *Journ. Philos., Psychol. & Sci. Meth.*, iii., 1906, 352 (Report of Sec. of N. Y. Acad. of Sciences), the report reads: "After-images were perceived, almost without exception, as far out as any color could be distinguished, and in many cases were clearly seen though the stimulus color was not recognised."

[13] *Psychol. Review,* XII., 408. Italics ours.

85.5° Red seen once, no color seen once.
87° *Red seen twice,* no color seen twice.

The conditions can hardly have remained constant from 74.5° to 87°. Again, R on Hering gray no. 7 is seen colorless at 37°, while it is seen red at 39°, 41.5° (twice), and even at 47° (twice).[14] And yet again, G on the same gray is seen colorless at 82°, green at 84°, and once colorless and once green at 87°.[15] Instances of this irregularity might easily be multiplied.

2. If we turn to the special table for the limits of B and Y, we find a greater uniformity of result, but a certain arbitrariness in the selection of the limiting values. Thus, on various backgrounds and for different observers, the limits for Y are taken as

(*a*) 97°, although at 98.5° the color is seen 3 times out of 14,
(*b*) 88.5°, although at 92.5° the color is seen once in 3 times,
(*c*) 95.5°, although at 98.5° the color is seen once in 3 times,
(*d*) 92.5°, although at 95.5° the color is seen 3 times out of 10,

and so on. Similarly, the limits for B are taken as

(*a*) 88.5°, although at 91.5° the color is seen once in 4 times,
(*b*) 97°, although at 99.5° the color is seen once, and one observation is doubtful,
(*c*) 97°, although at 99.5° the color is seen 3 times out of 9, with one observation doubtful,

and so on.[16]

Now in her second paper, of 1908, Miss Fernald states that the paradoxical after-images "are perceived most frequently either just inside or just beyond the regular limits for the color."[17] If this statement may be applied to the limits of color vision at large, *i. e.,* to the work of 1905, we must conclude that the crucial experiment has not been adequately performed; for the limits given are, as we have seen, irregular and arbitrary.

Each, however, if we maintain that *T*'s results are conclusive for the Bk–W zone, we have still to account for the colored after-images of subliminally colored stimuli in the B–Y and R–G zones.[18] Miss

[14] *Ibid.,* 422.
[15] *Ibid.,* 416.
[16] *Ibid.,* 402.
[17] *Psychol. Review,* XV., 33.
[18] Miss Fernald uses the term "unperceived," not subliminal. The latter word is, however, employed by the Misses Thompson and Gordon, whose results Miss Fernald assimilates to her own. That "unperceived" really means "imperceptible" is shown also by a passage in a letter received from Miss Fernald: "I should be very much afraid of my observer's life, if it depended on his identification of the stimulus color, in all cases in which a clearly colored after-image is seen. In fact, when forced to say what stimulus he thought was used, he guessed at B for O as often as O for O, insisting all the while that he did not see any color."

Fernald has been good enough to send us an account of the conditions under which her observers found the after-image, and to make a special series of observations, with Mr. C. E. Ferree as observer. "The head," she says, "must be held firm (my method is the bit, with the impression of the teeth). The background must be light, and the illumination good. The observer must hold the fixation steadily after the stimulus is removed. The after-image screen must be white to obtain Y or B after-images and black to obtain R after-images. A very slight change in conditions makes a great difference in results, which seem to me to depend wholly on brightness." Professor Baird was acquainted with these conditions before he undertook his perimetrical observations.

The new set of observations is as follows.

Observer: C. E. Ferree. Full illumination on bright day (May 17, 1908). Nasal meridian, right. White ground. Projection field white, except in obs. 14–17, when it was black. Stimulus, 13 sq. mm. Distance from eye to stimulus, 25 cm.

Fixation Point.	Stimulus.	Color Seen.	After-image.
80°	O	Dark gray	Unsaturated light blue
85°	B	Just dark	Wash of unsaturated yellow
85°	Y	Nothing	Nothing
80°	Y	Tinge of dirty yellow	Very pale blue
80°	Medium gray	Dark	White
80°	O	Indefinite gray	Nothing
80°	Light gray	Dark	White
75°	Y	Reddish yellow	Good blue
75°	B	Good blue	Good yellow
75°	B	Good blue	Good yellow
65°	O	Yellowish red	Unsaturated blue
65°	Y	Reddish yellow	Blue
60°	G	Indefinite greenish gray	Uncertain
65°	G	Greenish yellow	Dark red, more saturated than stimulus
80°	Medium gray	Dark	Nothing
80°	Medium gray	Dark	Nothing
65°	G	No color	Flash of red
65°	R	No color	Blue

Positive results occur in the two first and two last observations of the series. The former may be explained in terms of chromatic adaptation. If, as the illumination suggests, the observer began the

work in Y-adaptation,[19] the first, blue after-image would naturally follow. If the second observation was taken at too short an interval of time, the resulting B-adaptation would show itself as a yellow after-image. The two final observations suggest a shift of conditions. G is seen at 65° as greenish yellow, and as colorless; at 60° as indefinite greenish gray. It is possible that, in the case in which "no color" is reported, the G simply escaped notice; peripheral colors at the limit of vision often appear as momentary flashes. Again, R is reported at 65° as "no color," although "reddish yellow" had been seen as far out as 75°. It is possible that the flash of red escaped notice; it is also possible that R-adaptation, from the preceding after-image, brought out the blue.

The puzzling thing is that the positive outcome should be thus definite in the Mount Holyoke and Bryn Mawr laboratories, while neither Professor Baird nor ourselves—though working with full knowledge of conditions, and though trying various possibilities which have not been reported in detail[20]—are able in a single case to obtain the colored after-image. We can only guess at an explanation; and we offer the following guesses in what seems to us to be the order of their likelihood: (1) chromatic adaptation;[21] (2) the momentary and flash-like appearance of colors at the limit of vision; (3) the phenomenon of "fluctuation of attention"; (4) defective method and unsystematic procedure in the determination

[19] These observations were taken "after the limits had been roughly determined in previous experiments." If the defermination of limits was made at the same sitting, and if the last test-color employed was O, there would be additional reason for an initial Y-adaptation.

[20] Thus, Mr. Ferree wrote to us: "After-images seem to occur most intensively when the stimulus is removed while adaptation is still going on. If one carries the stimulation to a stationary point in adaptation, the after-image will weaken in proportion to the length of time during which the stimulus is regarded before the after-image is evoked. This is true whether one uses intensive or slightly supraliminal stimuli." We thought that it might possibly be true of subliminal stimuli, and accordingly made brief observations both in light and in dark adaptation. But we never saw the after-image.

[21] On chromatic adaptation, see Baird, *op. cit.*, 57 ff., 64 ff., 73 f.; *Journ. Philos., Psychol. & Sci. Meth.*, II., 1905, 21.

of zonal limits; (5) unnoticed variations, physical, physiological or psychological, in the conditions of observation during a series.[22]

We are well aware that negative experiments are logically inconclusive.[23] The fact that we have failed to find the colored after-image does not prove that this after-image is non-existent. We have, however, attempted a positive explanation: for Tschermak's result, in terms of prepossession and inaccurate method; for Miss Fernald's result, in terms (predominantly) of chromatic adaptation. Further experimentation by other observers must show whether our hypotheses are correct.

We are aware, also, that the charge of prepossession is double-edged, and that we may ourselves be accused of an initial bias. We freely confess that we, as well as Professor Baird, approached the peripheral experiments in a sceptical attitude of mind. On the other side, we may point out that the scepticism was positively based upon the results of Baird's Carnegie Institution research, and that the student-observers at the University of Illinois knew nothing of the question at issue.

In the case of Tschermak's observation, however, our initial bias was positive; we were surprised at the uniformly negative character of our results with the Marbe mixer. Tschermak's position seemed to accord well with current visual theory. Moreover, we knew that a contrast-color may be more saturated, may appear more "real," than the inducing, objective color. We knew that Heymans, in his experiments on "psychische Hemmung," had sometimes seen the contrast-color while the inducing color was still unperceived.[24] We knew of Helmholtz' statement, "dass die gesät-

[22] In a letter to *T* Miss Fernald remarks: "You will see that colored after-images were seen in less than one third of the total number of cases in which the stimulus-color was not seen." In a communication made to Professor Baird, she estimates, roughly, that the phenomenon appeared in about five per cent. of her exposures upon the peripheral retina. This sporadic and fortuitous character of the after-images suggests that they are the product of some variable condition which has not been taken account of in the investigations.

[23] J. S. Mill, "A System of Logic," 1884, 515; W. S. Jevons, "The Principles of Science," 1900, 434.

[24] G. Heymans, Untersuchungen über psychische Hemmung, i. *Zeits. f. Psychol. u. Physiol. d. Sinnesorgane,* XXI., 1899, 328. "Wo mit weissen Sectorenscheiben experimentirt wurde, kam es öfters vor, dass ehe noch der Ring die Farbe des Papierstückes erkennen liess, sich im Hintergrunde schon die Contrastfarbe bemerklich machte."

tigsten objectiven Farben, welche existiren, die reinen Spectralfarben, im unermüdeten Auge noch nicht die gesättigste Farbenempfindung hervorrufen, welche überhaupt möglich ist, sondern dass wir diese erst erreichen, wenn wir das Auge gegen die Complementärfarbe unempfindlich machen." [25] There was, then, no *a priori* reason to doubt Tschermak's result; on the contrary, we thought it probable that under conditions which were unfavorable to the appearance of the stimulus-color, but favorable to the appearance of its complementary, the subliminally colored stimulus would give a perceptibly colored after-image.[26] As a matter of fact, it did not.

[25] "Physiol. Optik," 1867, 370; 1896, 520. *Cf.* W. Wundt, "Physiol. Psychol.," II., 1902, 146.

[26] This possibility was considered, also, in the peripheral work; so that even for that our bias was not wholly negative.